

IS THERE A METALLICITY-LUMINOSITY RELATIONSHIP IN ACTIVE GALACTIC NUCLEI? THE CASE OF NARROW-LINE SEYFERT 1 GALAXIES

OHAD SHEMMER¹ AND HAGAI NETZER¹

Received 2001 November 14; accepted 2002 January 22; published 2002 February 8

ABSTRACT

The well-known relationship between metallicity and luminosity in active galactic nuclei (AGNs) is addressed by introducing new metallicity measurements (based on the method of Hamann & Ferland, hereafter HF) for a sample of narrow-line Seyfert 1 galaxies (NLS1s). Our new results, based on a sample of 162 AGNs, including nine NLS1s, indicate that while broad-line AGNs trace a metallicity–luminosity power law with an index of ~ 0.2 , NLS1s deviate significantly from this relationship at low luminosities. Adopting the HF method based on the N V/C IV line ratio, we find that NLS1 metallicities are similar to those of some high-redshift, high-luminosity quasars. We also examined the N IV]/C IV line ratio and compared it with N V/C IV in a sample of 30 sources including several NLS1s. We find that the two do not give a consistent answer regarding the N/C abundance ratio. This result is marginal because of the quality of the data. We suggest two alternative explanations to these results: 1) The HF metallicity–luminosity dependence is not a simple two-parameter dependence and there is an additional hidden variable in this relationship that has not yet been discovered. The additional parameter may be the accretion rate, the age of the central stellar cluster or, perhaps, something else. 2) The strong line ratios involving N V $\lambda 1240$ suggested by HF are not adequate metallicity indicators for NLS1s and perhaps also other AGNs for reasons that are not yet fully understood.

Subject headings: galaxies: abundances—galaxies: active—galaxies: nuclei—galaxies: Seyfert

1. THE METALLICITY-LUMINOSITY RELATIONSHIP IN ACTIVE GALACTIC NUCLEI

Studies of emission lines in active galactic nuclei (AGNs) indicate that metallicities are typically near the solar value in their broad-line region (BLR). Accurate determinations are difficult to obtain since the line ratios depend on unknown densities and optical depths (Netzer 1990). However, Shields (1976) showed that some BLR abundances can be derived from the observed line ratios of weak nitrogen, carbon, and oxygen lines, almost independent of the physical properties of the gas (see Hamann et al. 2002 for more details). One such line ratio is N IV] $\lambda 1486$ /C IV $\lambda 1549$ with a theoretical value of ~ 0.045 for solar metallicity. Others are N III] $\lambda 1750$ /O III] $\lambda 1663$, O III] $\lambda 1663$ /C IV $\lambda 1549$ and N III] $\lambda 1750$ /C III] $\lambda 1909$, which can determine the N/O, O/C, and N/C abundances, respectively. This method has been used in several AGN studies (e.g., Baldwin & Netzer 1978; Osmer 1980; Uomoto 1984), but there are practical limitations due to the weakness of these lines.

An important development in this area was achieved by Hamann & Ferland (1993, hereafter HF93; see also Hamann & Ferland 1999), who suggested alternative abundance indicators that are somewhat model dependent but much easier to obtain observationally. In particular, they have shown that the N V $\lambda 1240$ /C IV $\lambda 1549$ and N V $\lambda 1240$ /He II $\lambda 1640$ line ratios represent the overall BLR metallicity. They also claimed that BLR metallicity tends to grow with AGN luminosity up to $\sim 10Z_{\odot}$, thus implying a metallicity–luminosity (hereafter Z–L) relationship, in analogy with the mass–metallicity relationship observed for elliptical galaxies. At one extreme end of this relationship one finds the luminous and high-redshift quasars as AGNs having the highest metallicities. In several cases, those quasars display relatively narrow UV emission lines (e.g., Osmer 1980; Warner et al. 2002).

The low-luminosity regime in the HF93 diagram is also oc-

cupied by narrow-line Seyfert 1 galaxies (NLS1s) that have been mostly left out from previous abundance analyses. These NLS1s are defined by their extremely narrow optical permitted emission lines ($\text{FWHM} \lesssim 2000 \text{ km s}^{-1}$) in comparison with normal broad-line AGNs (BLAGNs; Osterbrock & Pogge 1985). NLS1s show extreme AGN properties; their optical emission lines put them at one extreme end of the Boroson & Green (1992) primary eigenvector, and they tend to display unusual behavior in other wave bands, especially in the X-ray (e.g., Boller, Brandt, & Fink 1996; Leighly 1999a, 1999b). A possible explanation for the peculiar properties of NLS1s is that they have relatively low black hole (BH) masses for their luminosities and hence a very large L/L_{Edd} . Since only a handful of NLS1s had their BH mass measured directly using reverberation mapping techniques (Peterson et al. 2000), this is not yet fully confirmed. Another extreme NLS1 property was recently suggested, namely, unusually high metallicities (Mathur 2000 and references therein). However, to date, this evidence remains scarce, and no systematic abundance study has yet been carried out.

In this study we present for the first time metallicity (\'a la HF93) measurements for a sample of NLS1s. In § 2 we define the sample properties and data analysis. In § 3 we describe our new results on the Z–L relationship in AGNs and attempt to answer two related questions: (1) Do NLS1s have higher metallicities compared with BLAGNs for a given luminosity? (2) Are the higher metallicities, assumed for NLS1s related to the fundamental physical properties that drive the NLS1 phenomenon?

2. SAMPLE PROPERTIES AND DATA ANALYSIS

We selected 162 type 1 AGNs, including nine extreme NLS1s, that had either published optical or UV (*HST*) HF93 line ratios or an UV (*HST*-archived) good-quality spectrum

¹ School of Physics and Astronomy and the Wise Observatory, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel; ohad@wise.tau.ac.il, netzer@wise.tau.ac.il.

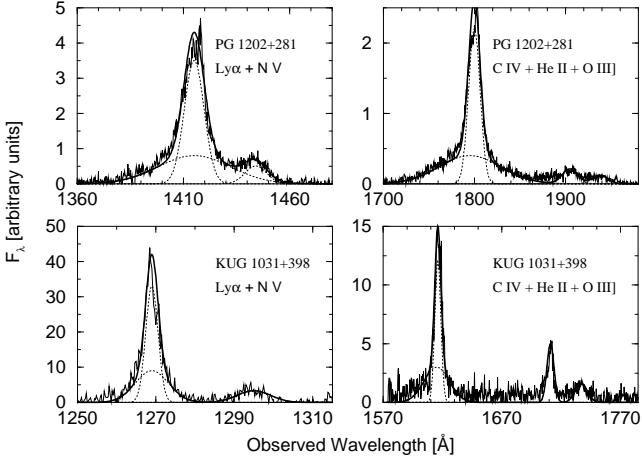


FIG. 1.— Two typical line-fitting examples: A BLAGN PG 1202+281 (*top panels*) and an NLS1 KUG 1031+398 (*bottom panels*). In each continuum-subtracted spectrum, the Ly α region (*left panels*) and the C IV region (*right panels*) were fitted as explained in the text. In each panel a thin solid line represents the spectrum; dotted lines represent the individual Gaussian profiles that are then summed to form the entire fit to the spectrum (*thick solid lines*).

covering the rest-frame range of $\sim \lambda\lambda 1200$ –1700. We also inspected UV(*IUE*) spectra of 11 extreme NLS1s, but the poor signal-to-noise ratios resulted in line flux uncertainties that were too large to be included in our study (although the general trend was similar to the nine NLS1 spectra taken from *HST*). A redshift of $z \approx 1.6$ defines the transition from low- z objects, for which the relevant emission lines are detected in the UV, to those objects for which N V is detected in the optical band and are hereafter referred to as high- z quasars. We consider NLS1s as AGNs having $\text{FWHM}(\text{H}\beta) \lesssim 1500 \text{ km s}^{-1}$ in order to concentrate on the more extreme objects of this class².

Among the 162 objects, 67 have published optical spectral data and are regarded as high- z and unknown $\text{FWHM}(\text{H}\beta)$ objects (Osmer & Smith 1976, 1977; Baldwin & Netzer 1978; Osmer 1980; Uomoto 1984; Baldwin, Wampler, & Gaskell 1989; Baldwin et al. 1996; Dietrich & Wilhelm-Erkens 2000). All those include detailed line intensity measurements. The rest, 95 low- z objects, including the nine extreme NLS1s, have UV (*HST*) spectra. Of these, 44 have published line intensities (Reichert et al. 1994; Laor et al. 1994, 1995, 1997; Wills et al. 1995). Emission-line fluxes of 111 objects were thus readily available for our analysis. For the remaining 51 objects, we obtained the HF93 line ratios by performing line and continuum measurements on the archived spectra by applying a multi-Gaussian component fit using the NGAUSSFIT task in IRAF³. For Ly α and C IV $\lambda 1549$, two Gaussian components were fitted, while for N V $\lambda 1240$, He II $\lambda 1640$, and O III] $\lambda 1663$ we fitted a single Gaussian. Two typical fits of this kind appear in Figure 1. The individual fits produced uncertainties on the line fluxes that were much smaller compared with the uncertainties introduced by other unknowns, such as the precise continuum placement and slope, line contamination, etc. In particular, the Si II $\lambda 1264$ complex might be expected to contribute at most $\sim 20\%$ (Laor et al. 1997) to the N V $\lambda 1240$ intensity only in AGNs with $\text{FWHM}(\text{N V}) \gtrsim 5000 \text{ km s}^{-1}$. In light of the underestimated uncertainties, we compared published flux values with new measurements that we performed for several

² H β is the most suitable emission line for distinguishing broad-lined BLRs from narrow-lined ones. Measurements of $\text{FWHM}(\text{H}\beta)$ are not available for $\sim 60\%$ of our sample's objects that have $z \gtrsim 0.5$. Throughout this Letter, we treat those unknown $\text{FWHM}(\text{H}\beta)$ objects as BLAGNs.

³ IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

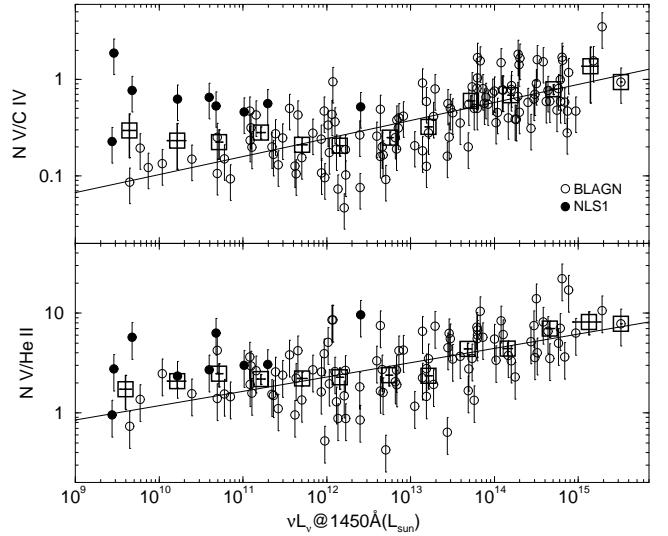


FIG. 2.— HF93 metallicity indicators, N V/C IV (*top*) and N V/He II (*bottom*), as a function of luminosity. Empty circles mark BLAGNs, and filled circles mark NLS1s; solid lines represent the BLAGN best-fit $Z - L$ slope; large squares with error bars represent average line ratios in bins of 0.5 in $\log \nu L_\nu$ of the entire data set. Note the significant deviation of the low-luminosity bins from the straight line (*top*) owing to the addition of NLS1s.

test cases and concluded that uncertainties on the line fluxes we measured can nominally be taken as 30%. Finally, we included only positive measurements of line intensities, excluding a few cases of upper flux limits, that did not alter our basic finding as discussed below. We were therefore left with 130 (107) positive measures of the N V/C IV (N V/He II) line ratios. Luminosities were derived from the monochromatic flux at $\lambda 1450$, taking $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

Our sample is far from being statistically complete. However, we do not know of any observational or selection effect that will bias the sample against strong N V lines (that are easily detectable and measurable). In particular, our sample of UV (*HST*) sources is strongly biased in favor of radio-loud quasars (e.g., Wills et al. 1995). To test this effect, we carried out the analyses as discussed below while excluding line ratios of the radio-loud population. Our results were not significantly affected by this test (see § 3). Thus, while the following correlation slopes may depend on the specific sample, the important result (the fact that low-luminosity sources show very strong N V/C IV; see § 3) is insensitive to that.

3. RESULTS AND DISCUSSION

3.1. New Correlations Involving N V $\lambda 1240$

Figure 2 shows the N V/C IV (*top*) and N V/He II (*bottom*) line ratios as a function of luminosity. The HF93 line ratios of the entire sample were also binned in ranges of 0.5 in $\log \nu L_\nu$ to minimize the effect of uneven distribution in luminosity. The average positions of all objects in each of those bins are shown as large squares with error bars in Figure 2. The error bars on the large squares represent, for each axis, the standard deviation divided by the square root of the number of objects in each bin. For each HF93 line ratio– νL_ν log-log diagram, we performed a linear regression analysis and calculated the Pearson and Spear-

TABLE 1
LINEAR REGRESSION PARAMETERS FOR N V/C IV VERSUS LOG νL_ν

Data Set Code ^a	Number of Objects	Pearson (r)	Spearman (r_s)	Slope (a)	Constant (b)
B	121	0.70	0.73	0.19 ± 0.02	-2.86 ± 0.23
B+N	130	0.55	0.60	0.13 ± 0.02	-2.11 ± 0.23
RQQ (B)	105	0.72	0.74	0.18 ± 0.02	-2.82 ± 0.23
RQQ (B+N)	114	0.56	0.60	0.13 ± 0.02	-2.04 ± 0.24
B+up.lim.	137	0.67	0.69	0.19 ± 0.02	-2.91 ± 0.24
B+N+up.lim.	146	0.52	0.57	0.13 ± 0.02	-2.17 ± 0.24

^aData set codes are B for BLAGNs, N for NLS1s, RQQ for radio-quiet quasars, and up.lim. for upper limits on the line ratio.

TABLE 2
LINEAR REGRESSION PARAMETERS FOR N V/HE II VERSUS LOG νL_ν

Data Set Code ^a	Number of Objects	Pearson (r)	Spearman (r_s)	Slope (a)	Constant (b)
B	98	0.58	0.60	0.14 ± 0.02	-1.37 ± 0.27
B+N	107	0.50	0.53	0.11 ± 0.02	-0.95 ± 0.24
RQQ (B)	83	0.61	0.64	0.14 ± 0.02	-1.25 ± 0.26
RQQ (B+N)	92	0.54	0.57	0.11 ± 0.02	-0.87 ± 0.23
B+up.lim.	110	0.54	0.55	0.15 ± 0.02	-1.45 ± 0.28
B+N+up.lim.	119	0.46	0.48	0.11 ± 0.02	-1.00 ± 0.26

^aData set codes are identical to those in Table 1.

man linear correlation coefficients. This analysis was carried out once for the BLAGN population and a second time for the entire data set. The results are presented in Tables 1 and 2; one can see that the exclusion of radio-loud objects or the addition of flux ratio upper limits (that were treated as real ratios) had little effect on the correlations and slopes.

Inspection of Figure 2 and Tables 1 and 2 shows that the N V/C IV ratio is strongly correlated with luminosity in the BLAGN case. However, it is also apparent that this relationship *breaks down completely* at low luminosities, when the NLS1s are introduced into the sample. Several NLS1s that belong in the lowest luminosity regime even have N V/C IV ratios as high as those of the most luminous high-z quasars. The extremely strong N V $\lambda 1240$ in some NLS1s has been noted earlier by Wills et al. (1999) who did not investigate the resulting N/C abundance ratio. The N V/He II ratio behaves somewhat differently when NLS1s are added (Fig. 2). We find that the N V/He II ratio in BLAGNs is correlated with luminosity, although not as strong as in the N V/C IV case, and that NLS1s only slightly deviate from the N V/He II $Z-L$ slope. We also discover that both line ratios are not correlated with luminosity for νL_ν at $1450\text{\AA} \lesssim 10^{46}$ erg s $^{-1}$, neither for BLAGNs nor for the entire sample. We emphasize once more that the N V/C IV ratio in NLS1s is very similar to the one observed in high- L AGNs and this result, which is based on an easy-to-measure line ratio, is enough to completely change the original HF93 correlation, regardless of the exact slope or value of the correlation coefficient.

3.2. High N V/C IV at Low Luminosity

Our new results point at two distinct scenarios: either (1) the HF93 line ratios overpredict N/C at least under some physical conditions or (2) high metallicities at low luminosities are possible and are seen in NLS1s. We discuss briefly the implications of these two scenarios and defer the more detailed analysis to a later publication.

3.2.1. Is the N V/C IV Line Ratio a Reliable N/C Indicator?

Hamann et al. (2002, hereafter H02) have used state-of-the-art photoionization calculations to investigate several line ratios in order to select those that are robust abundance indicators. The calculations span a vast range of densities [7 \leq

$\log n_{\text{H}}(\text{cm}^{-3}) \leq 14$] that completely cover the typical range attributed to the broad emission line gas in AGNs [$\log n_{\text{H}}(\text{cm}^{-3}) \approx 10$]. Since there is no evidence for densities as large as 10^{13} – 10^{14} cm $^{-3}$ in NLS1s, we have no reason to suspect that they lie outside the range covered by the H02 calculations. According to the calculations, the N V/C IV line ratio is a reliable N/C indicator over the range of interesting physical conditions expected in the BLR. H02 have also considered several of the weak intercombination lines, such as N III] $\lambda 1750$ /O III] $\lambda 1663$ and N IV]/C IV, previously discussed by Shields (1976), and concluded that the first is more reliable than the second, as it is less sensitive to the model assumptions. Results for all relevant line ratios are shown in their Figure 4 and a specific application to the locally optimally emitting clouds (LOCs) model is shown in H02 Figure 5.

The only other line ratio available to us, except for the N V/C IV ratio discussed above, is N IV]/C IV. We have therefore investigated the N/C obtained from the two line pairs both observationally and theoretically. Several BLAGNs of our sample had published flux values (or upper flux limits) of the weak line N IV]. We added to this subsample measurements of the N IV] line in eight of our nine extreme NLS1s. The N/C abundance obtained from the N IV]/C IV line ratio was then calculated for the subsample, assuming that upper limits represent real ratios. We find that the two line ratios are well correlated ($r = 0.8$ for 30 sources); i.e., if N V/C IV is a good N/C indicator, so is N IV]/C IV. However, the derived N/C, *assuming both ratios are reliable metallicity indicators*, is very different. The N V/C IV ratio gives systematically larger N/C, sometimes by a factor as large as 3 or 4. We stress that the results are still tentative because of the large number of upper limits rather than real line ratios used in the analysis. Better data are required to confirm this correlation.

Regarding the suitability of N IV]/C IV as an N/C indicator, we note that the calculations presented in Figure 4 of H02 show that the line ratio does not change by more than a factor of 2 over the range of conditions thought to be acceptable in AGN BLRs (ionization parameter of 0.03–0.3 for the H02 continuum and density below about 10^{12} cm $^{-3}$). The H02 conclusion that the line ratio is not a robust N/C indicator is based on regions in parameter space that are different from the one specified above. Moreover, the particular example shown in Figure 5 of H02, applicable to the LOC model, clearly shows that under such conditions (that produce well most of the observed line ratios in AGNs; see Baldwin et al. 1995), the N IV]/C IV line ratio is indeed a very good N/C indicator. A key issue is whether or not the physical conditions in the BLR of NLS1s are similar to those in broader line AGNs. The idea that density and optical depths may be different has been proposed in the past, and a better assessment of the N IV]/C IV suitability in this case must await a more detailed theoretical investigation of such sources. At present we do not have a large enough sample and good enough calculations to test the suggestion that the results shown in Figure 2 are due to N V/C IV being an inadequate N/C indicator.

3.2.2. High-Metallicity NLS1s?

The second scenario is based on the assumption that the N V/C IV is a reliable N/C indicator. This led HF93 to suggest a strong $Z-L$ relationship in AGNs. However, our new measurements clearly show that NLS1s do not follow this $Z-L$ relationship. NLS1 metallicities, as indicated by the N V/C IV ratio, are

similar to those of the most luminous high- z quasars in our sample and are higher, by almost an order of magnitude, than those of BLAGNs with similar luminosities. In the N V/He II case, NLS1s show only slightly higher metallicities for a given luminosity compared with BLAGNs. This effect may be attributed to the more complex dependence of N V/He II on other physical parameters, such as the spectral energy distribution. Accepting this scenario, the HF93 $Z-L$ relationship cannot be a simple two-parameter dependence for all AGNs.

We also attempted to find a link between BLAGNs and NLS1s in order to see whether the $Z-L$ relationship is a smooth function of FWHM(H β). We found no correlation between FWHM(H β) and metallicity, luminosity, or a combination of the two. Since we have FWHM(H β) values for about half of our sample, we checked whether FWHM(C IV) could be more suitable, since this emission line is more dominant in our case. Again we found no correlation with the other parameters, nor any FWHM(C IV)–FWHM(H β) correlation, for objects having both lines measured. In fact, we find that only AGNs that have FWHM(H β) $\lesssim 1500 \text{ km s}^{-1}$ follow a significantly different $Z-L$ relationship.

If high metallicity is indeed another NLS1 extreme property, the question whether this is related to some fundamental NLS1 physical parameter remains unanswered. The introduction of NLS1s to the N V/C IV $Z-L$ diagram completely changes the correlation at low L and implies that there is an additional dimension to this dependence that allows high metallicities at low luminosities. This hidden variable in the $Z-L$ relationship may be related to fundamental physical properties, such as the accretion rate or the age of the central BH. The key to answering this question possibly lies in the claim that NLS1s have low BH masses for their luminosities (equivalent to larger L/L_{Edd} or higher accretion rate) and therefore follow a different mass-luminosity relationship than BLAGNs (Peterson et al. 2000). Boroson & Green (1992) pointed out that L/L_{Edd} might be the underlying fundamental physical property of their primary eigenvector. Since NLS1s lie at one extreme end of this eigenvector, a natural hypothesis is that this property is also driving their unusually high metallicities. In order to test this hypothesis, one needs accurate BH mass determinations for our sample. Unfortunately, those are available

for only 34 objects (Kaspi et al. 2000), including only three extreme NLS1s. Moreover, measuring BH masses for high- z quasars is not a straightforward task since reliable determinations rely on reverberation mapping studies that would require at least a decade-long monitoring campaign due to cosmological time dilation. In addition, measurements of [O III], optical Fe II, and H β lines in high- z quasars are scarce (e.g. McIntosh et al. 1999).

3.3. The $Z-L$ Relationship in BLAGNs

Finally, we remain within the framework of the second scenario, where the HF93 line ratios are considered reliable abundance indicators and NLS1s show systematically higher metallicities than BLAGNs with comparable luminosities. We therefore removed all NLS1s from the sample and checked the $Z-L$ relationship for BLAGNs [we caution the reader that the BLAGN group includes objects with unknown FWHM(H β); see § 2]. Our results confirm the observational evidence for a correlation between metallicity and luminosity (HF93) for a large (statistically incomplete) sample of BLAGNs. This correlation may be written in the form $Z \propto L^\alpha$, where Z and L are the BLR metallicity and BLAGN luminosity, respectively. Since both N V/C IV and N V/He II are approximately proportional to Z (HF93), the index is assigned with the mean value obtained for our sample, which is $\alpha \sim 0.2$ (Tables 1 and 2). Combining this result with the empirical AGN BH mass-luminosity relationship (Kaspi et al. 2000), $M_{\text{BH}} \propto L^{0.5}$, we find $Z \propto M_{\text{BH}}^{0.4}$. Alternatively, one may argue that the (Kaspi et al. 2000) result regarding the L versus M relation is biased because of the small size of the sample, and a more realistic form is perhaps $M_{\text{BH}} \propto L$. In this case, $Z \propto M_{\text{BH}}^{0.2}$. These results differ from those that were reached by supermassive BH growth considerations where α was assumed to take a value of ≈ 0.5 (Wang 2001). We note, again, that the above obtained α depends on the sample selection and is, therefore, rather uncertain.

This research is supported in part by a grant from the Israel Science Foundation. We thank an anonymous referee for useful comments and suggestions.

REFERENCES

- Baldwin, J. A., Ferland, G., Korista, K., & Verner, D. 1995, ApJ, 455, L119
- Baldwin, J. A., & Netzer, H. 1978, ApJ, 226, 1
- Baldwin, J. A., Wampler, E. J., & Gaskell, C. M. 1989, ApJ, 338, 630
- Baldwin, J. A., et al. 1996, ApJ, 461, 664
- Boller, T., Brandt, W. N., & Fink, H. 1996, A&A, 305, 53
- Boroson, T. A., & Green, R. F. 1992, ApJS, 80, 109
- Dietrich, M., & Wilhelm-Erkens, U. 2000, A&A, 354, 17
- Hamann, F., & Ferland, G. 1993, ApJ, 418, 11
- . 1999, ARA&A, 37, 487
- Hamann, F., Korista, K. T., Ferland, G. J., Warner, C., & Baldwin, J. 2002, ApJ, 564, 592
- Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, ApJ, 533, 631
- Laor, A., Bahcall, J. N., Jannuzi, B. T., Schneider, D. P., & Green, R. F. 1995, ApJS, 99, 1
- Laor, A., Bahcall, J. N., Jannuzi, B. T., Schneider, D. P., Green, R. F., & Hartig, G. F. 1994, ApJ, 420, 110
- Laor, A., Jannuzi, B. T., Green, R. F., & Boroson, T. A. 1997, ApJ, 489, 656
- Leighly, K. M. 1999a, ApJS, 125, 297
- . 1999b, ApJS, 125, 317
- Mathur, S. 2000, MNRAS, 314, 17
- McIntosh, D. H., Rieke, M. J., Rix, H.-W., Foltz, C. B., & Weymann, R. J. 1999, ApJ, 514, 40
- Netzer, H. 1990, in Active Galactic Nuclei, ed., T. J.-L. Courvoisier & M. Mayor (Berlin: Springer), 57
- Osmer, P. S. 1980, ApJ, 237, 666
- Osmer, P. S., & Smith, M. G. 1976, ApJ, 210, 267
- . 1977, ApJ, 213, 607
- Osterbrock, D. E., & Pogge, R. W. 1985, ApJ, 297, 166
- Peterson, B. M., et al. 2000, ApJ, 542, 161
- Reichert, G. A., et al. 1994, ApJ, 425, 582
- Shields, G. A. 1976, ApJ, 204, 330
- Uomoto, A. 1984, ApJ, 284, 497
- Wang, J.-M. 2001, A&A, 376, L39
- Warner, C., Hamann, F., Shields, J. C., Constantin, A., Foltz, C. B., & Chaffee, F. H. 2002, ApJ, 567, 68
- Wills, B. J., Laor, A., Brotherton, M. S., Wills, D., Wilkes, B. J., Ferland, G. J., & Shang, Z. 1999, ApJ, 515, L53
- Wills, B. J., et al. 1995, ApJ, 447, 139